Formal Analysis and verification of Arrival Procedure for an Aircraft using Petri nets

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Abstract: Air Traffic Control (ATC) is safety critical real times service in Air Traffic Management (ATM) where system correctness is a major concern, and which requires high degree of confidence and targets zero failure rates to avoid loss of human lives and other disastrous (unfavorable) conditions. The ever increasing volume of air traffic may cause unwanted delays in the flight during the arrival procedure of the aircrafts. Hence, there is an absolute need to formally model and verify the arrival procedure of the aircrafts to avoid delays and to assure the controlled coordination between aircraft and air traffic controllers which are involved in this process. In this paper, we have modeled the arrival procedure of the aircraft using Petri nets which have been used traditionally as a rationale for formal specification and verification for such a safety critical systems. The proposed model assures how the behavior of acting objects affects the overall procedure of arrival management. Moreover, we have verified the proposed model using coverability tree as an analysis method that ensures the deadlock-freeness and reliability of the mechanism involved between the aircraft and the air traffic controllers (ramp controllers and ground controllers) for the arrival of the aircraft.
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1. Introduction

Air Traffic Control is a traffic control service governed and regulated by Federal Aviation Administration (FAA is an agency of United States Department of Transportation (http://www.faa.gov/) that regulates and overseas the different aspects of civil aviation in the U.S) like any other service in ATM. Managing the arrival traffic in ATC system is one of the most challenging tasks, although different automated tools have been used in ATC system that supports the human operators to achieve their operational goals. These tools are helpful in number of ways i.e. increasing their exposure with the outside environment, sequencing plans for arrival and departure of the aircrafts, calculating the target times on a specific point for the aircrafts, finding conflict free routes, giving the planned instructions for clearance of the aircrafts, alerting restricted areas, adjusting threshold between runways etc. But inspite of the presence of these automated tools, these tasks are heavily dependent on human intervention and rely on human perception, understanding, decision making and coordination [1-2], thus throwing the safety risks on human controllers. According to Hollnagel, Woods and Leveson [3], it is the inherited spirit of the system that makes it safe but in air traffic control system, the capabilities and performance (right act at right time) of the human controllers makes the system safe and reliable. They have to regularly reach a tradeoff between efficiency and thoroughness, if they are to be successful [4-6]. With the increasing air traffic volume, this tradeoff also applied to arrival procedure of the Air Traffic Control system. Another problem arises when the aircrafts do not meet their targeted flight times and delays are observed in arrival times or there are multiple aircrafts arriving at the same time. The problem is to maintain a safe distance between them and direct them for safe arrival by avoiding any hazardous situation and safety issues. Many factors that cause safety issues and affect the safety in ATC system have been discussed in [28] [29].

Hence, to counteract the impact of these safety hazards the formal analysis and verification of the safety critical systems is necessary to verify the safety properties and to prevent the loss of human lives due to their malfunctioning. There must be some control strategy to formally design and develop the safety critical systems to investigate the impact of human intervention on the underlying system and to verify the proper functioning of the mechanism involved [7]. Studies show that the formal methods have been used for requirement specification, analysis and verification of different aspects of ATC system i.e. system domain analysis, modeling the human intervention, identifying problems caused by human intervention, identifying different components of ATC systems, modeling the departure process and avoiding delays in the arrival procedure etc. [7-13].

We have used Petri nets as a formalizing technique to model the arrival procedure due to the discrete nature of the system. Petri nets have great motivation to be used for the formal analysis and verification of the discrete event control systems, distributed systems, concurrent systems, time sharing systems etc. to identify their functional behavior and verify their system properties [14-17]. As compared to other formal methods, Petri nets have the ability to develop the graphical representation of the system from the logical sequencing of the system that shows the flow of information in the system. It provides the simulation capabilities that are used to verify the dynamic behavior of the system at any given time before the implementation. Further, the mathematical foundation of the Petri nets can be used to make qualitative and quantitative analysis of the system properties. Moreover, Petri net have been used as a formal modeling technique for analyzing the safety properties and to identify the associated risks in ATC system e.g. the process of cooperative arrival planning, modeling human interaction, flight sequencing plans, conflict resolution etc [1][6][18-22].

In this paper, we have modeled the arrival procedure for an aircraft that is a supervised and controlled procedure (sequence of steps) between three acting and controlling bodies (aircraft, ramp controller and gate controller). The ramp controllers and gate controllers are air traffic controllers that have their designated portion in the designated airspace where they are responsible for managing the air traffic flow by following basic guidelines and control instructions given by FAA [23]. The aircraft initiates the process requesting the ramp controller to enter the ramp area. The ramp controller acts as a supervisory control and centralized coordination body that allows the aircraft to enter the ramp area and sequences it on the ramp queue. Then the control is transferred to gate controller which assigns the gate (if available) to the aircraft and finally passes it from the gate to the exit. The proposed model verifies the functional behavior of the underlying system and makes sure that the arrival procedure follows the guidelines and controlled instructions regulated by FAA for the arrival procedure given in [24]. It further assures the reliability of the system by verifying the safe, sound and timely arrival of the aircraft. It provides timely support and coordination between the aircraft and the air traffic controllers.

The rest of the paper describes the Petri nets and related concepts in Section 2. It then explains the modeling of arrival procedure using Petri net model in Section 3. Section 4 presents the analysis and verification of the arrival procedure to identify system properties. Finally, section 5 concludes our work.

Table 1: Arrival Procedure for an Aircraft in ATC

	Actions	Pre-Conditions	Post-Conditions
Aircraft	The aircraft requests to the ramp controller to enter the ramp area.	1. Aircraft must be registered. 2. The aircraft must have not requested for ramp yet. 3. The aircraft must be on taxi way.	1. Add the aircraft in those aircrafts who have send request to enter the ramp area.
Aircraft	The aircraft will enter the Ramp Area	1. The aircraft must be registered. 2. The aircraft must have clearance to enter the ramp area by ramp Controller	1. The aircraft is entered into Ramp Area. 2. Discard Permission to enter ramp area for this aircraft.
Aircraft	The aircraft will request for Gate Assignment to Gate Controller.	1. Aircraft must be registered. 2. Aircraft must be in Ramp queue. 3. Aircraft must not in the list of aircrafts who have already requested for a gate assignment. Aircraft must not already assigned gate.	1. Request for gate assignment is confirmed by gate controller. 2. Gate is assigned by the gate controller.
Aircraft	The aircraft will request to gate controller to pass gate	1. Aircraft must be registered. 2. Aircraft must not be in the list of Aircrafts who have applied for request to pass gate. 3. Aircraft must be already be assigned gate.	1. Aircraft will be added in queue of request to pass from gate.
Aircraft	Aircraft will pass from gate	1. Aircraft must be registered. 2. Aircraft is not in pass gate queue. 3. Check if the aircraft have permission to pass from gate by gate controller.	1. Aircraft now pass from the gate. 2. Discard permission for gate pass for this aircraft. 3.Requesttopush back is cancelled
Aircraft	Aircraft Finally arrived	1. Aircraft must be registered. 2. Aircraft must be in pass gate queue. 3. The aircraft must not be in set of aircrafts that have reached.	1. Aircraft is in set of Reached Aircrafts. 2. The aircraft is now exited from pass gate queue.
Ramp Controller	It grants Permission to enter ramp is granted to aircraft.	1. The aircraft must be registered. 2. The aircraft must not belong to those aircraft which have clearance to enter ramp.	1. Clearance is granted to the aircraft. 2. The request of the aircraft is discarded to enter ramp area.

		3. The aircraft has already sent request for entering ramp.	
Ramp-Controller	It Sequence the aircrafts at ramp area	1. Aircraft must be registered. 2. The aircraft must be in ramp area. 3. Make sure that aircraft is not in the ramp queue.	Promote \add aircraft to the ramp queue.
Gate Controller	It assigns gate to the aircraft.	1. The aircraft which has sent request for gate assignment must not be assigned gate already. 2. Check the status of the gate if free the gate will be assigned	Aircraft is assigned gate
Gate Controller	It grants the permission to the aircraft to pass from the gate	1. The aircraft should not already have clearance to pass from gate. 2. The aircraft must be registered.	Clearance is given to the aircraft to pass from gate.

2. Definition and Concepts related to Petri nets

In this section, some basic definitions and notations of Petri nets are described. Further, some important concepts needed for the rest of the paper are also discussed in this section.

Definition 1: (*Place/Transition-net)*[25], [26] a finite capacity, ordinary place/transition (P/T)-net, is a five tuple, $PN = (P, T, I, O, K, M_0)$ where $P = \{p_1, p_2, \ldots, p_{|P|}\}$ is a finite set of places, $|P| > 0$; $T = \{t_1, t_2, \ldots, t_{|T|}\}$ is a finite set of transitions, $|T| > 0$; $I : T \to P$ is the input function which is a mapping from transitions to the sets of their input places; $O : T \to P$ is the output function which is a mapping from transitions to the sets of their output places; $K : P \to \mathrm{N} \cup \{\omega\}$ which gives the capacity to each place; where $P \cap T = \varnothing$ and $P \cup T \neq \varnothing$.

For a transition $t_j \in T$, $I(t_j)$ and $O(t_j)$ represent the sets of *input and output places* of t_j respectively. A place $p_i \in P$ is the input place of a transition t_j if $p_i \in I(t_j)$ and the output place of t_j if $p_i \in O(t_j)$.

The input and output functions can be extended to map the set of places P into the set of transitions T such as $I : P \to T$ and $O : P \to T$. Then, $I(p_i)$ represents the set of *input transitions* of place $p_i \in P$ and $O(p_i)$ represents the set of *output transitions* of place $p_i \in P$.

Definition 2: (*Firing rule*) [25], [26] the firing rule identifies the transition enabling and the change of marking. A mapping $M : P \to \mathrm{N} \cup \{\omega\}$ is called a marking of the net if and only if $M(p_i) \leq K(p_i)$ for all $p_i \in P$, then for $\forall t_j \in T$; t_j is enabled under marking M if and only if $\forall p_i \in I(t_j)$: $M(p_i) \geq 1$ and $\forall p_i \in O(t_j) : M(p_i) \leq K(p_i) - 1$. The change of marking M to M' by firing the enabled transition t_j is denoted by $M[t_j\rangle M'$ and defined for each place $p_i \in P$ by $M'(p_i) = \begin{cases} M(p_i) - 1 \text{ for every } p_i \in I(t_j) \\ M(p_i) + 1 \text{ for every } p_i \in O(t_j) \\ M(p_i) \text{ otherwise.} \end{cases}$

Definition 3: *(Reachability)* [25], [26] A marking M_k is said to be reachable from marking M_0 if there exists a sequence of transition firings that transforms M_0 to M_k. In the case when M_k is reachable from M_0 by σ we write $M_0[\sigma\rangle M_k$.

Definition 4: (*Boundedness and safeness*) [25], [26] for all $p_i \in P$ of PN (N, M_0), PN is *b-bounded* if $\forall M_k \in R(M_0)$: $M_k(p_i) \leq b$ and said to be *safe* if $M_k(p_i) \leq 1$.

Definition 5: (*Deadlock and deadlock free*) [25], [26] A transition $t_j \in T$ is said to be dead transition at marking $M_k \in RM(M_0)$ if there is no reachable marking to make transition t_j enabled. A marking $M_k \in RM(M_0)$ is said to be a deadlock if $\forall t_j \in T$, t_j is dead. A PN (N, M_0) is said to be deadlock-free if and only if there is no deadlock.

3. Petri net Model of the Arrival Procedure for an Aircraft

We used Petri nets as a formal modeling, analysis and verification tool to model the proposed methodology for the arrival of an aircraft in the airport. Following assumptions have been made while modeling the arrival procedure.

- Aircraft is already a registered aircraft.
- Pilot, Ramp controllers and Ground Controllers are aware of all environmental and configuration settings of the airport and have knowledge of Arrival procedure of ATC system [24].
- Pilot, Ramp Controllers and ground controllers are aware of defined policies and basic rules regulated by Federal Administration Authority (FAA) [23].

- Air traffic controllers has effective source of information related to unfavorable circumstances.

We have developed the Petri net model (see Figure. 1) for the arrival procedure of an aircraft using Petri net Toolbox [27]. In Figure 1, key actors (aircraft, ramp controller and ground controller) are shown in the form of three objects representing by three states (Aircraft, Ramp cntrl, Gate cntrl). The key terms and terminologies about ATC system and the arrival procedure e.g., Taxiway, Ramp, Runway etc can be found on [23] [24]. The Places Ramp cntrl, Gate cntrl are set to an infinite capacity, to show that there can be more than one objects for ramp controller and ground controller that coordinate with the aircraft. We have set the capacity of one (1) for the rest of the places including the place 'Aircraft', which ensures the safe arrival of the aircraft by not allowing the simultaneous arrival of the aircrafts.

As the procedure starts, the aircraft must be on the Taxiway that is shown by place p4. In the given model, the place with the name 'Start' started the procedure and it is used to ensure that the aircraft has sent request for the first time. During the arrival procedure, aircraft is added in different queues i.e. (request queue for ramp, ramp queue, request queue for gate assignment and to pass gate and gate pass queue) according to the scenario. The queues have been maintained in the developed model using set of places {p5, p6, p10, p11, p12, p15}. All other places have been mapped to store the results\status of the preceding transitions (see Table 2 for complete specification of all the places).

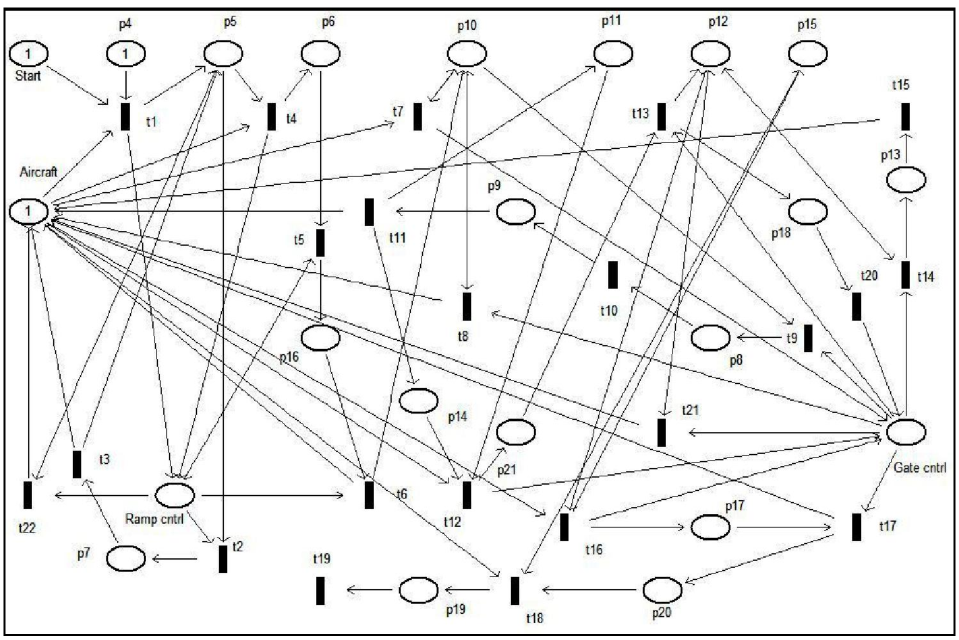

Figure 1: Petri net Model of Arrival Procedure of an Aircraft in ATC

In the proposed model, different transitions have been mapped to different actions (sending requests, discarding and granting permission, assigning and adding in relevant queues) and these actions are fired by three actors according to the situation. The set of seven (07) transitions {t1, t4, t7, t12, t16, t18, t19} have been used to map the actions, as given in 1(a) and (b) part. These actions are taken by the aircraft during the arrival process respectively i.e. requesting to enter the ramp, entering the ramp, requesting for gate assignment, requesting for gate pass, passing from gate and finally arrived and exited from the ramp area. The proposed model ensures the effective communication between the controllers and the aircraft by sending acknowledgement\status messages at the end of every successful scenario.

In Figure 1, the required actions taken by the ramp controller (in response to aircraft's request) to enter the ramp area is shown by the set of transitions {t2, t3, t5, t6, t21, t22} (see Table 3 for the specification of the transitions). The gate controller coordinates with the aircraft by granting permission for gate assignment and allows the aircraft to pass from the gate by firing the set of transitions {t8, t9, t10, t11, t12, t13, t14, t15, t17}. The transition t20 is used to transfer control back to the gate controller, once the aircraft has been added in the request queue for gate pass. The proposed model ensures the smooth working and deadlock-freeness of the procedure involved in the arrival of the aircraft.

Table 2: Specification of the Places given in Figure 1

Places	Interpretation	Places	Interpretation
Aircraft (p1)	It acts as an aircraft object	p11	It act as request queue for gate assignment
Ramp cntrl (p2)	It acts as Ramp controller object	p12	It acts as request queue to pass gate
Gate cntrl (p3)	It acts as a gate controller object	p13	It stores the status of the clearance for the aircraft to pass gate.
Start	It acts as a start place and ensures that the aircraft requests for the first time to enter ramp area.	p14	It stores the status of gate assignment.
p4	Aircraft is on taxiway	p15	Aircraft is in gate pass queue.
p5	It acts as request queue for ramp area	p16	It shows the request of permission of aircraft is discarded to enter ramp area
p6	Aircraft is on ramp area	p17	It stores the status of aircraft to pass from gate
p7	It stores the status of clearance of the aircraft for entering the ramp area.	p18	It stores the status of request of aircraft is added in queue to pass from gate
p8	It stores the status of the gate when it is free.	p19	Aircraft will land
p9	It stores the status of request of gate assignment is confirmed.	p20	It stores the status of Permission is discarded to pushback
p10	Aircraft is in the ramp queue.	p21	It acts as an intermediate place\buffer to store the request coming from aircraft for passing gate.

Table 3: Specification of the Transitions given in Figure 1

Transitions	Interpretation	Transitions	Interpretation
t1	It is used to send request to ramp controller to enter the ramp area by aircraft.	t13	It shows the request of aircraft is added in the queue to pass gate
t2	It shows aircraft has not clearance to enter into ramp area.	t14	It checks the clearance for the aircraft to pass the gate and resulted in false case means Aircraft does not have clearance already.
t3	It is used to grant permission to aircraft to enter into ramp area	t15	It shows permission is granted to aircraft to pass gate by gate controller
t4	It shows aircraft is entered into ramp area	t16	It shows aircraft is passed from gate
t5	It discards permission to enter ramp area once aircraft is entered into ramp area	t17	It shows Permission is discarded for gate pass to this aircraft and pushback request is cancelled
t6	It is used to sequence the aircraft in ramp queue by ramp controller.	t18	It shows aircraft is arrived
t7	It shows that aircraft sends request for gate assignment.	t19	It shows aircraft is exited
t8	It shows gate is not free for the assignment to aircraft.	t20	It transfers control back to gate controller
t9	It shows gate is free for the assignment to aircraft.	t21	It shows aircraft already have clearance to pass gate.
t10	It shows request of gate assignment is confirmed.	t22	It shows aircraft have already clearance to enter into ramp area
t11	It shows gate is assigned to aircraft by gate controller.		
t12	It shows aircraft sends request to gate controller to pass gate		

4. Formal Analysis and Verification of the Proposed Petri net Model

Formal analysis and verification is a key to make a comprehensive analysis of system properies and to assure its correctness and reliability. This reliability is needed in arrival procedure to avoid hazardous situations and unwanted delays. It is needed to maintain the proper sequencing and planning for arrival between the aircrafts during flights. The proposed methodology shows that the behavior of controllers is dynamic according to the scenerios (see Table 1 for details) at any given moment. The state space analysis method (coverability tree) is used to verify proposed mothodology given in Figure 1.

The proposed model maintains proper and effective communication between the aircraft and air traffic controllers, by transferring valid information. The modelled system ensures the reliablity by avoiding to reach a state where no further communication can be made between the objects (Aircraft, Ramp cntrl and Gate cntrl) . Second, we have modeled the system in a way to avoid the forbidden states which can lead to bugs in the proposed model. Moreover, the acting objects (Aircraft, Ramp cntrl and Gate cntrl) are reactivated to their initial states according to the result of previous scenerio to take further actions.

Figure 2 shows the reachability (coverability) tree of the proposed model of Figure 1. It is assumed initially, that the aircraft is a registered and is making first time request to enter the ramp area and is currently on Taxiway. Hence, the places 'Start' and 'Aircraft' are marked and is represented by the initial marking

M0 = Aircraft + Start + p4

In Figure 2. following an initial marking M0, the aircraft sends request to ramp controller to enter the ramp area leading to the marking M1 given below.

M1= Ramp cntrl + p5

At marking M1, ramp controller takes the control to check the clearance status of the aircraft, allowing the aircraft to enter the ramp area represented by marking **M4 (Aircraft + p6)**. Then ramp controller sequences the aircraft and discards permission for this aircraft, once it is on ramp and transfers control again to the aircraft. This process is represented by the following markings.

M5 = (Ramp cntrl + p16)

M6 = (Aircraft + p10)

The aircraft then requests for gate assignment to the gate controller represented by the marking **M7(Gate cntrl + p10).** Now, the gate controller takes necessary actions (see Table 1) to assign the available gate to the aircraft and allows the aircraft to pass from the gate after making some control checks for gate clearance and transferscontrol back to the aircraft. All these steps are represented by the following markings:

M8 = Aircraft + p10	**M9 = p8**
M10= Aircraft + p11+ p14	**M11 = Gate cntrl + p21**
M12 = p12+p18	**M13 = Gate cnrtl + p12**
M14 = p12 + p13	**M15 = Aircraft + p12**
M16 = Gate cntrl + p15+ p17	**M17 = Aircraft + p15 + p20**

The marking M19 (dead state\last step) shows that the aircraft has been finally arrived and exited (see Figure 2 to see all the reachable markings and corresponding firing sequence during the arrival process).

Analysis of the given model, ensures the safeness property (discussed in Definition 4) of the proposed methodology as the number of token in every place remains bounded (less then or equal to one) for every marking M reachable from initial marking M0. This further ensures, the reliability of the mechanism involved by making informed decisions . The proposed model is deadlock-free, (discussed in Definition 5), all transitions are potentially (at least once) fireable that gurantees the correctness of involved mechanism. It also assures the effective communication between aircraft and traffic controller, without creating any bottleneck during the process.

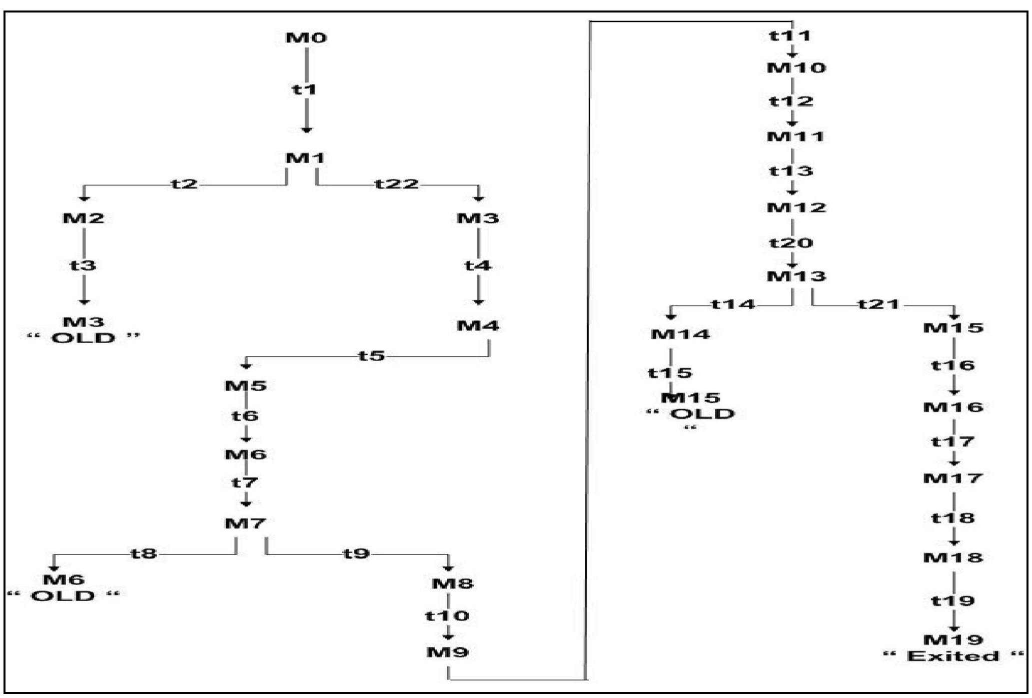

Figure 2: Coverability Tree of Arrival Procedure for an Aircraft in ATC

3. Conclusions

Formal methods have been used to provide a primary and concrete basis for safety critical and fault tolerant systems. They have been used to verify the critical decisions taken for safety critical systems. Petri nets provide strong basis to verify functional reuirements and to model dynamic aspects of the underlying system before actual implementation starts. Petri nets have been used for the verification of the system properties to avoid the gaps between system design and its implementation. We have used Petri nets to automate the behavior of the arrival procedure of an aircraft and acting objects before it is deployed in its working environment. The whole process is coordinated by the help of air traffic controllers involved in the arrival processThe proposed model effectively handled the control decision points, taken by three acting bodies (aircraft, ramp controller and gate controller) according to the configuration and environmental settings observed at that time. The proposed model avoided the safety issues by not allowing to reach a state where no further actions can be taken. Finally, the purposed model was further analyzed by using coverabiltity tree (reachability graph) to assure the consistency, correctness and reliability of the proposed mechanism.

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